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Research paper

Modeling a Direct Contact Heat Exchanger used in a supercritical water loop

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HIGHLIGHTS

- Modelling the thermodynamic behavior of a Direct Contact Heat Exchanger.
- Steam cooled by liquid droplets coming from a spray.
- Predictions are reasonable for steam pressures lower than 2.1 MPa.
- The effect of the droplet distribution functions is studied.
- A new correlation that fits the data at higher pressures is proposed.

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ABSTRACT

In the last thirty years, Direct Contact Heat Exchangers (DCHX) have found a great success in different power engineering applications. In fact, due to the direct contact of hot and cold working fluids, it is possible to reach very high mass and energy transfer efficiencies. Despite their high performance, it is still difficult to predict the correct heat transfer as a function of plant operating conditions. Thus, this paper concerns the study of a DCHX used in a supercritical water test facility. It consists of a vessel where superheated steam is cooled by mixing it with sub-cooled water via a nozzle that sprays the fluid under the form of tiny droplets. A thermodynamic model which includes the statistical distribution of droplets and their temperature evolution is presented. To this aim, a Cumulative Distribution Function (CDF) based on Rosin–Rammler's equation is used. To evaluate both convection and evaporation energy transfer, the evolution of the velocity of the droplet as function their size is studied. A comparison of model's predictions with experimental data, for steam pressures of 1.6 and 2.1 MPa, shows reasonable good agreement. At higher pressures the model over predicts the experimental trends.

1. Introduction

Direct Contact Heat Exchangers (DCHX) which use spray nozzles are extensively encountered in numerous industrial applications, amongst other in nuclear power stations, cooling towers, petroleum, thermal and chemical plants [12,17]. For this reason and in order to predict the performance of DCHXs, both the heat and mass transfer from liquid droplets have been largely studied.

Marshall [12] studied the effects of droplet size into the heat and mass transfer from a liquid spray to the air during air-drying processes. In his modeling approach, the droplet evaporation rate is explicitly included in the energy balance equation. Based on experimental data, Marshall proposed a correlation for the Nusselt number (*Nu*) as function of Reynolds (*Re*) and Prandtl (*Pr*) numbers. Sripada et al. [9,16] presented a model by assuming spherical droplets in the conservation equations. Based on this approach, they estimated the behavior of key physical properties, i.e. surface tension σ, droplet surface velocity v, *Nu* and surface shear stress τ, as a function of time and droplet angular position.

Ref. [5] studied the behavior of the droplet temperature in contact with a condensing steam environment. As initial conditions, they considered the droplets at the sub-cooled liquid

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temperature and the surrounding vapor at saturation. Assuming conduction heat transfer inside the droplet, they calculated the spray-droplet mean temperature by solving the energy conservation equation obeying the initial values. Furthermore, to achieve a better agreement of the predictions of the model with experimental data, they introduced the effect of liquid circulation inside the droplet by a coefficient that depends on the Péclet's number. Ref. [17] compared the predictions obtained using the model of Celata et al. [15] with their own experimental data and thus, they were able to show that this model is not adequate to evaluate the liquid temperature for non-dimensional distances lower than 6 (the non-dimensional distance is defined as $X = x/D$, where x is the distance from the nozzle and D a characteristic droplet diameter).

When liquid is sprayed into a gas atmosphere, it should be expected that the droplets will have different physical dimensions; therefore the use of a Cumulative Distribution Function (*CDF*) is mandatory. Moreover, the CDF becomes a key function when condensation and/or evaporation occur, because these two processes affect their physical dimensions and consequently their dynamics. By using statistical moments as a function of time to compute the *CDF* and including droplet collisions and break-up mechanisms, Ref. [3] were able to determine the evolution of droplet sizes. However, a simpler way to compute the *CDF* consists of using droplet size distribution laws, as those proposed by Rosin–Rammler or Nukiyama–Tasanawa as given in Ref. [7]; in conjunction with empirical correlations to estimate factors required by these laws. One of these factors corresponds to the Sauter mean diameter (D_{32}) that is estimated as Ref. [1]:

$$D_{32} = \frac{\sum_{i=1}^{N} n_i D_i^3}{\sum_{i=1}^{N} n_i D_i^2} \tag{1}$$

This equation represents an order of magnitude of the ratio between the entire volume (subscript 3) occupied by the droplets and their entire surface area (subscript 2). Several correlations are available in the open literature that allows D_{32} to be determined. For instance, to estimate D_{32} [10] has proposed several correlations as a function of the geometry of the nozzle and the thermodynamic inlet liquid flow conditions.

In this paper, a thermodynamic model has been developed to estimate the heat transfer rate in a *DCHX* currently installed in a supercritical water test facility, identified as the "Quenching Chamber" in Fig. 1. The main purpose of this thermal equipment consists in cooling the superheated steam coming from a test section, which is used to perform choking flow experiments with water above supercritical conditions [13]. As shown in the figure, the cooling water is sprayed and mixed with the steam in order to reach the highest possible heat and mass transfer.

Since the sizes of the droplets depend on the type of nozzle (i.e. its geometry) and the temperature of the injected water, the *CDF* is estimated using a methodology that is presented in the following section. Thereafter, the heat transfer from the steam to the liquid, both by convection and evaporation is introduced into the calculations. Finally, the predictions obtained applying the proposed approach are compared with experimental data collected under three system pressures during supercritical water choked-flow experiments [13].

2. Droplet size distribution function

In order to the predict heat transfer in *DCHX*s, an appropriate estimation of droplet sizes is necessary, however, this is not an easy task. In fact, the droplet size distribution function depends on many factors, including the liquid temperature, the liquid flow rate and the geometrical characteristic of the nozzle [10,15]. To this purpose, several statistical laws are proposed in the open literature, which provide distribution functions for liquid particles (e.g. log-normal, Nukiyama–Tasanawa, upper-limit, root-normal, etc.). One of the simplest laws available is the Rosin–Rammler cumulative distribution function, where the probability of having droplet volume fractions for droplets with diameters smaller than a given diameter D is given by Ref. [11]:

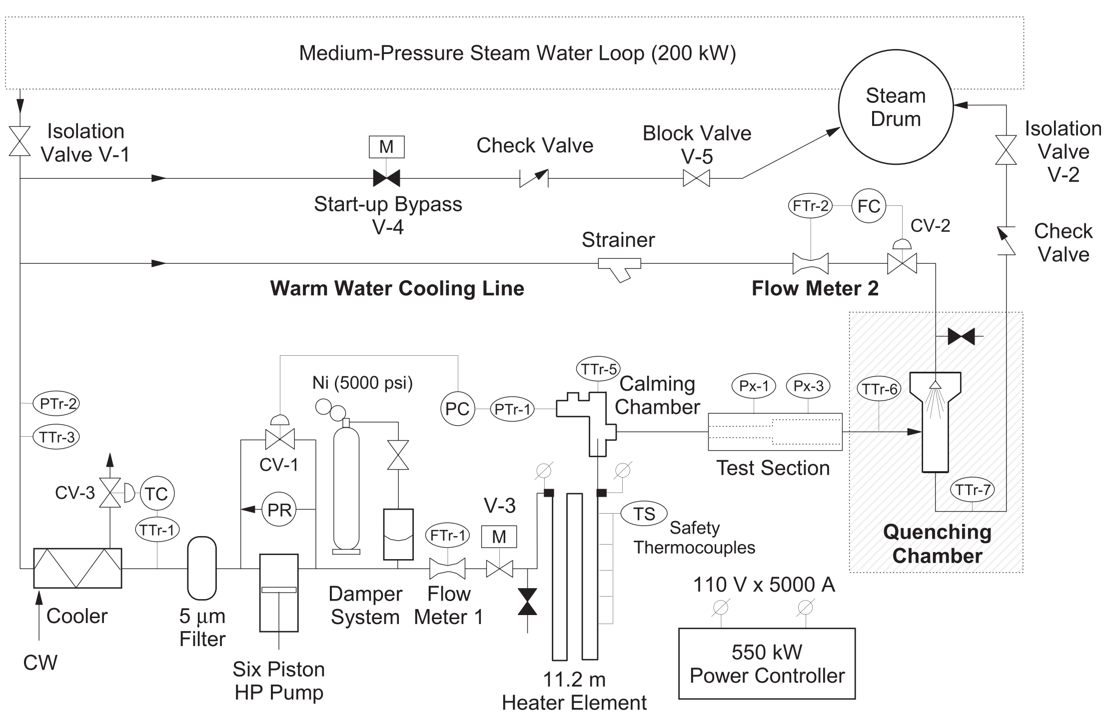

Fig. 1. Flow diagram of the supercritical water facility.